ULTRASONIC INSPECTION OF ACOUSTICALLY "NOISY" MATERIALS

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INTRODUCTION

Ultrasonic inspection of large gas turbine rotor forgings made of IN706 (40Ni-15Cr-Ti-Nb superalloy) is complicated by the material's anisotropic and nonuniform acoustic properties. These properties stem from the intrinsically coarse grain structure of IN706 in forgings weighing up to 22,000 pounds and having axial and radial dimensions up to 20 inches and 90 inches, respectively. Although recent advances in the melting and forging processes have helped to improve the material's microstructure, many characteristics still preside which make ultrasonic inspection a challenge. The inspection and signal processing techniques described herein compensate for variations in the acoustic properties that we have observed from forging to forging as well as within any given forging. These techniques may be applied to a wide variety of applications dealing with acoustically noisy materials with nonuniform acoustic characteristics.

The forgings receive an ultrasonic inspection in three principle orthogonal directions: axial, radial and tangential. The axial and radial inspections are accomplished by longitudinal wave, pulse-echo, contact testing from all outside surfaces. A tangential test is performed in regions of high operating stresses using a shear wave, through-transmission, contact test from the axial surfaces of the forging. This test is called the "pitch-catch" test. In addition, longitudinal and shear wave, pulse-echo, immersion tests are performed, on turbine wheel forgings only, from inside the bore.

This paper presents a description of the above tests with the exception of the immersion tests from inside the bore.

INSPECTION HARDWARE

The inspection system is comprised of a 486 PC computer system operating with a processor speed of 66MHz, a GE AMPUT^{tm} logarithmic flaw detector, and encoded mechanical drive equipment to rotate the forgings. For each pulse of the transducer, the full-wave rectified waveform is acquired at a sampling rate of 25 MHz. All test data are recorded on an optical disk and automatically evaluated in a post-processing mode.

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Five axes of computer controlled motion are required to control the movement of the forging and search units. Scanning is performed by rotating the forging while the transducers remain stationary. Unfocussed search units are used for all tests performed. The transducers are pulsed eight times as the forging rotates through an arc length equal to the 6dB sound beam width.

The ultrasonic signals are acquired from an ultrasonic flaw detector that was custom built by GE with a logarithmic amplifier. Three decades are used (60 dB), ranging from 1% to 1000% of the logarithmic scale. Use of the logarithmic instrument greatly increases the dynamic range of amplification over conventional instruments with linear amplifiers. An 8-bit analog-to-digital converter is used to acquire the ultrasonic waveform for the axial and radial tests. Only the peak amplitude within the intersection volume is acquired for the pitch-catch test.

TEST DESCRIPTIONS

All of the tests performed on the IN706 forgings use a calibration method that is independent of external reference reflectors. Part specific references are used to normalize the test data and equate the amplitude of indications to known reflectors so that the test sensitivity or size of indications can be uniquely determined for each test.

Because IN706 exhibits a relatively narrow bandpass, prior to each inspection, the Fourier Transform of an internal reference reflection is computed and compared to the search unit's unfiltered bandpass. An attempt is made to match the filtered and unfiltered bandpasses as closely as possible in order to maximize the test sensitivity.

Scan plans are determined prior to each test based on the forging dimensions and search unit frequency. The sound beam cross-section is calculated at each location in the forging. Data acquisition and scan increments are controlled to produce a near uniform sound field everywhere within the inspection volume. The maximum off-axis decrease in pressure amplitude between successive scan lines does not exceed 1 dB for the axial test, 3 dB for the pitch-catch test, and 4 dB for the radial test.

Axial and Radial Tests

The axial and radial tests use a longitudinal wave search unit operated in the pulse-echo mode. The complete volume of the forging is inspected by the axial test. Because the direction of material flow lines are mostly radial near the center of the forgings, only the outer one third of the forging is inspected by the radial test .

For the axial test, a unique calibration method is used to compensate for changes in material attenuation and anisotropy from forging to forging, as well as within the forging under test. Every sampled data point from each waveform acquired is normalized by the large reflection obtained from the opposite surface of the forging at that location. In this way, all test data automatically adjusts for changes in acoustic properties prior to further processing using the defect detection algorithms discussed in this paper.

Pitch-Catch Test

The pitch-catch test uses two shear wave angle beam search units operated in the transmit-receive mode. An illustration of the test setup is shown in Figures 1 and 2. The search units are directed toward an axial-radial plane of the forging. As the forging rotates, its axial-radial planes pass through the beam path intersection creating the inspection volume. After one rotation, a toroid of material has been inspected. The search units are then swept radially in unison to complete the inspection of one axial slice, or plane of material. To complete the process, the search units are moved relative to each other so that the beam path intersection moves axially across the forging.

Calibration of the test is accomplished by rotating one of the test search units by 180° and displacing it by approximately the forging thickness so that they are aiming directly at each other. A diagram of the calibration method is shown in Figure 3. The peak signal obtained is referred to as the through-transmitted sound wave. The placement of the search units is adjusted to maximize the amplitude of the through-transmitted sound wave. The angle θ is measured and used in the sizing equation along with the maximized amplitude of the through-transmitted sound wave. Calibration using this technique is equivalent to using the signal reflected from an infinitely large back wall reference surface oriented perpendicular to the test surfaces.

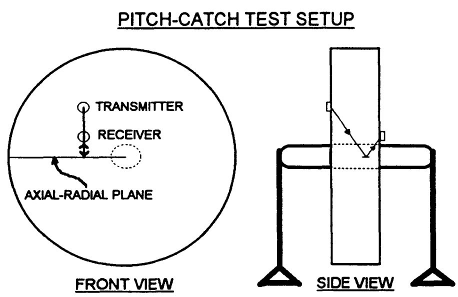

Figure 1 - Pitch-Catch test concept as performed on turbine rotor disk forgings.

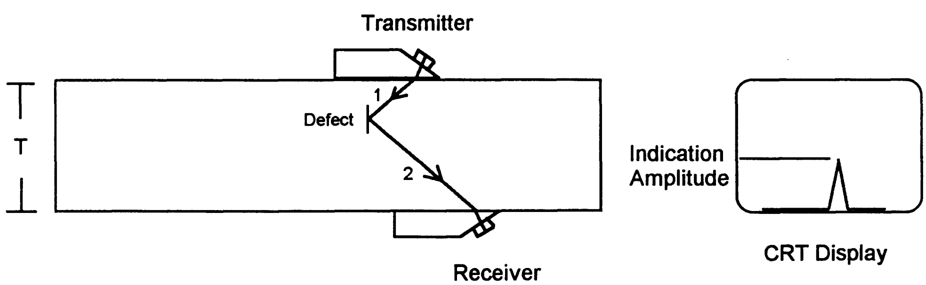

Figure 2 - Pitch-Catch test showing transducers and CRT display with defect.

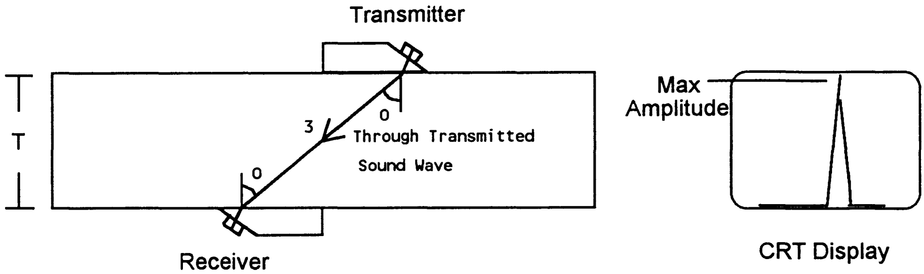

Figure 3 - Illustration of pitch-catch calibration through transmitted sound wave.

Studies have shown that the optimum search unit angle (θ) for best performance is approximately 40°. Although, based on equation (2), the maximum sound pressure relative to a defect would be obtained with a search unit angle equal to 45°; in practice a slightly lower angle is optimum. This occurs because the sound path distance within the forging is shortened, and hence the attenuation of sound between the search units is lower.

Prior to performing the actual pitch-catch inspection, a unique through-transmitted sound wave (through-wall reference signal) is obtained at many test locations on the forging. To be specific, a reference is taken every one inch in the radial direction and every one degree circumferentially on the forging. The data is normalized by the nearest reference signal amplitude prior to post-processing. By performing this normalization, variations in the acoustic properties within the forging are compensated for. The technique is based on the principle that the through-transmitted sound wave is affected by the material acoustic properties in the same way that the test data is affected. The through-transmitted sound wave is also used to equate the amplitude of indications to a known reflector (FBH) so that the test sensitivity or size of indications can be uniquely determined for each test.

<u>Sizing Equations</u>

<u>Axial and Radial Tests</u>

For indications detected by the axial or radial tests, equation (1) is used to calculate the equivalent flat bottom hole (EFBH) diameter of an indication based on the peak amplitude of reflected sound.

$$D_f = \sqrt{\frac{2Pvx^2}{\pi P_r fT}} \tag{1}$$

where
- D_f = EFBH diameter of the indication
- P = peak amplitude of the indication
- P_r = amplitude of back-wall reference at location of the indication
- v = longitudinal wave velocity of sound in the material
- x = distance to the indication
- T = axial thickness of the forging
- f = measured frequency of the back-wall reference signal

This expression is based on an approximate solution of the on-axis pressure distribution and is valid only in the far field, or beyond a distance from the transducer equal to three near field lengths. No correction is made for indications detected prior to the far field because, to a first order approximation, the error in neglecting attenuation effects tends to cancel the error due to the approximation of a linear pressure distribution.

Pitch-Catch Test

For the pitch-catch test, equation (2) is used to calculate the EFBH diameter of an indication based on the peak amplitude of reflected sound.

$$D_f = \sqrt{\frac{4Pvz(T-z)}{\pi P_r f T \sin(\theta)\cos(\theta)}} \qquad (2)$$

where
- D_f = EFBH diameter of the indication
- P = peak amplitude of the indication
- P_r = amplitude of through-wall reference at location of the indication
- v = shear wave velocity of sound in the material
- f = measured frequency of the through-wall reference signal
- z = distance of the indication from the nearest surface of the forging
- T = axial thickness of the forging
- θ = measured intercept angle between the search units

This expression is plotted in Figure 4 (labeled "uncorrected") for P=25%, v=0.125"/μsec, T=10", P_r=1000%, f=2.25 MHz and θ=40°. Note that the theoretical relationship between EFBH diameter and reflected sound pressure is independent of the transducer diameters that are used in the search units. In practice, however, the transducer diameter does affect this relationship due to the near and transit field non-linear pressure response.

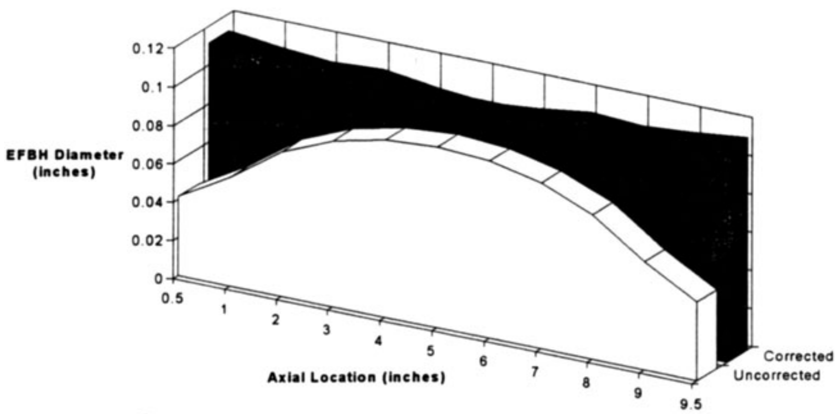

Figure 4 - EFBH verses axial depth at constant pressure.

To account for the nonlinear on-axis sound pressure distribution near the transducers, a correction is applied to the above determined EFBH diameter. This correction is based on empirical results that were obtained from fabricated test blocks and is also shown in Figure 4 (labeled "corrected"). Note that the theoretical expression for the EFBH diameter underestimates the actual flat bottom hole size, particularly near the test surfaces.

SUMMARY

Ultrasonic inspection of gas turbine rotor forgings made of superalloy IN706 is complicated by the large size of the forgings and the noisy and variable acoustic properties of IN706. All of the inspections performed by GE on these forgings have been automated to increase reliability and to optimize the probability of detecting defects. The methods and equipment presented in this paper summary have been used by GE to successfully inspect over 300 IN706 gas turbine rotor forgings to date.